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First Battle in the Heat: Physiological
Logistics For Success.
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There are two major physiologic requirements for optimum performance of troops during their initial actions in a hot theater of operation; previous heat acclimatization and previous planning for delivery and ingestion of adequate water. Heat acclimatization requires about 7 days, with about 2 hours each day spent doing moderately hard to heavy work under conditions at least as hot as those anticipated; lower levels of exertion and/or heat stress produce only partial acclimatization. Adequate replacement of body water, lost as sweat is also essential to prevent early physical and/or heat exhaustion of the troops. The USARIEM heat casualty prediction model (HEATCAS), developed to predict the physiological responses and their operational impact for acclimatized, well hydrated troops, has now been expanded to include the responses of unacclimatized troops, their improvements with acclimatization, the estimated drinking water requirements and the effects of failure to provide the required water. The model provides tabulated and graphical predictions of the benefits of heat acclimatization and the costs of dehydration on operations under any specified combination of climate and terrain. Some previous military operations, where inadequate initial acclimatization or water intake produced operational problems are compared with the USARIEM model predictions.

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FIRST BATTLE IN THE HEAT: PHYSIOLOGICAL
LOGISTICS FOR SUCCESS

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INTRODUCTION:

Even in civilian populations not required to perform hard work, excess mortality is produced by sudden increases in environmental heat; when air conditioners were inoperative during a four day heat wave in the summer of 1970 because of the power outage in New York City, there was increased mortality (2) despite relatively mild conditions ($T_{db}/T_{wb} = 33^\circ/23^\circ\text{C}$). The problem is much worse for the soldier, particularly the infantryman:

"The life of a foot soldier is divided between two extremes of labour and inactivity. Sometimes he is ready to sink beneath fatigue, when, having his arms, accoutrements and knapsack to carry, he is obliged to make long marches, especially in hot or rainy weather..."

John Pringle, 1752
Surgeon General to the English Army

Experience with such conditions led Medical officers nearly a century ago to postulate:

"If possible, choose the cool season for campaigns in warm countries."

Andrew Duncan, 1888
Surgeon to The Bengal Army

The passage of time has not altered these medical comments; if anything, loads are heavier, protective clothing (body armor, chemical

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protective clothing) more restrictive, troops must be selected from a less physically fit population, and they can be moved into hot environments rapidly, without time for the "seasoning" associated with slower movement by foot, rail or ship. A personal letter from Viet Nam in May, 1970, would have offered little new to Surgeons Pringle or Duncan, other than the use of aircraft:

"Last week I was up along the Cambodian border. Troop units (battalions) are being relocated and reshuffled to new areas; often without any or enough canteens. Short, i.e., 1-3 day, patrols need continuous air resupply, especially water. Air assets are in critical supply and are continuously working. In the space of a couple hours I saw 5 men of one squad dusted off back to the relocated base camp and several others from that one company dusted off for heat casualties--all within a couple hours on the 6th of May. The temperature was hotter than I'd ever experienced...in the adjacent FSB someone reported 126°F...as I departed about 4 PM that day, I heard there were more heat casualties on the way in.

...About 1/3 had severe cramps and 2/3 had severe weakness, palpitations, fever and near collapse...Incidently, this battalion had just (couple days earlier) been moved into this area from their old base...They had been fighting in relatively easy rice paddies (dry season) and were now required to hack their way thru thick jungle...big difference in terms of energy required."

LTC MC, USA
Viet Nam May 1970

Given the high work demanded, particularly during the first few days of engagement with an enemy, and the inability, given U.S. policy of non-aggression, to choose either the time or place of the first battle, there is a significant probability that U.S. troop units will again be required to move rapidly into a hot climate and fight a decisive battle within hours of arrival. The history of heat trauma as a war experience (15) adequately documents that the problem will not disappear. Given reasonably fit, trained and equipped troops, there are two major physiological factors which will seriously degrade the military operational capacity of the men; optimum performance requires previous heat acclimatization of the men; it also requires prior planning to assure delivery--and ingestion--of adequate drinking water. This paper addresses these two facets of preparation for a units first battle in the heat, and describes a validated computer prediction model to assess the effects of any lack of acclimatization and of any dehydration.

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HEAT ACCLIMATIZATION:

Heat acclimatization is a term used to describe changes in a number of different physiological parameters; taken all together, these changes which follow exposure to heat produce a major alteration in the soldier's ability to work in the heat (1,9,14). Although the separate elements in the heat acclimatization process can be induced by a variety of techniques, as described below, full heat acclimatization status is most evoked:

- a. with moderate work (e.g., marching with no load at 5.2 km/hr)
- b. with minimum clothing, if not in direct sunlight (to avoid the clothing limitation of evaporative cooling, and thus prolong march time before heat exhaustion occurs)
- c. with "luxus" drinking water (enough to replace sweat losses and thus avoid dehydration)
- d. with an environmental condition (temperature/humidity) at least as severe as that to be encountered operationally.

Acclimatization to less severe environments, or at lower work levels than will actually be encountered operationally, will produce only partial heat acclimatization for the operational situation. However, because it requires about 100 minutes of daily work in the heat to produce full acclimatization (with 50 minutes clearly less beneficial and 200 minutes producing little added benefit), the acclimatization exposures must start with either moderate work or reduced temperature/humidity conditions. This Institute's typical heat acclimatization regimen involves exposure at 49°C (120°F), 20% RH, marching at 5.6 km/hr for 100 minutes (usually two, 50 minute marches separated by a 10' rest break); the men wear shorts and combat boots (or sneakers). They ingest 1/2 canteen of water (500 ml) before the march and then are asked to drink at least 1/4 canteen (250 ml) at the middle and end of each 50 minute march and just before the end of their 10 minute rest. Total water intake is almost 2 full canteens (1.75L) during the 110 minute exposure, which just about equals sweat losses, since sustainable sweat production is about one liter per hour, with short term rates of 3 to 4 L/hr attainable.

In our experience, with probably over 1000 men, even with these optimum clothing and water and modest work conditions, few, if any of our subjects (modestly fit, garrison troops, 18-25 years old) could complete the full 100 minute march on the first day; we limit

these experimental exposures when body temperatures exceed 39.5°C (103°F) or heart rates exceed 180 to 190 b/m and, thereby, experience no heat stroke problems and only transient heat exhaustion episodes. Typically, as shown in Figure 1, on the first day our first man is removed after 30-35 minutes (usually unassisted) while the last man is removed after completing about half the second 50' march. A dramatic improvement is seen on the second day, with about 1/3 of the men completing the march. Each day, more men complete the 100 minutes and by the 6th or 7th day all are considered "fully acclimatized", except the usual 2 or 3% who appear to be "unacclimatizable"; these are almost always individuals who have a low maximum work capacity (which may be a genetic state resistant to physical conditioning, or may, less often, reflect inadequate physical conditioning). The extended tolerance times reflect decreases in heart rate, from 175 b/m after 50' of the first day's walk, to values at the 100th minute on the 4th day of 165 b/m; body temperatures also decrease, from 39.5°C at 50 minutes of the first day to <39°C at the end of the 6th or 7th day. As a very crude rule of thumb, about 33% of the total benefit from heat acclimatization is incurred with one day of exposure, the second day adds another 15-20%, the third another 10-15% and the fourth through sixth or seventh contribute about 10%/day to the fully heat acclimatized status.

Most of the mechanisms contributing to this state are known. The improved cardiovascular conditioning that is induced by working in the heat is a substantial contributor; while hard physical conditioning in comfortable environments can contribute substantially, and we estimate that a very fit soldier has the equivalent of about three days of heat acclimatization (12), the body's ability to deal with the problem of distributing its available blood supply between working muscles, where it picks up the heat produced, and a hot, fully vaso-dilated skin, where it attempts to eliminate this heat, can only be fully developed by working in the heat. An initial increase in circulating blood volume (hemo-dilution) during heat acclimatization also contributes to the decreased strain of work in hot environments; with chronic exposure to work in the heat (e.g., after a month or more) blood volume appears to return toward baseline levels. Another major facet of the heat acclimatization process involves conditioning of the sweat gland, and its control mechanisms, to begin to produce sweat at a lower skin temperature (i.e., $\leq 35^{\circ}\text{C}$) and to produce more sweat per gland, thus improving the body's potential for sweat evaporative cooling; these effects can be at least partially produced simply by heat, e.g., in saunas, hot baths or steam rooms. Another facet of the heat acclimatization process involves an increase in aldosterone levels so

WORK TOLERANCE IN HEAT DURING 7 DAYS ACCLIMATION

N = 24

TDB = 49°C (120°F)

TWB = 27°C (80°F) 20% RH

SPEED = 3.5 MPH

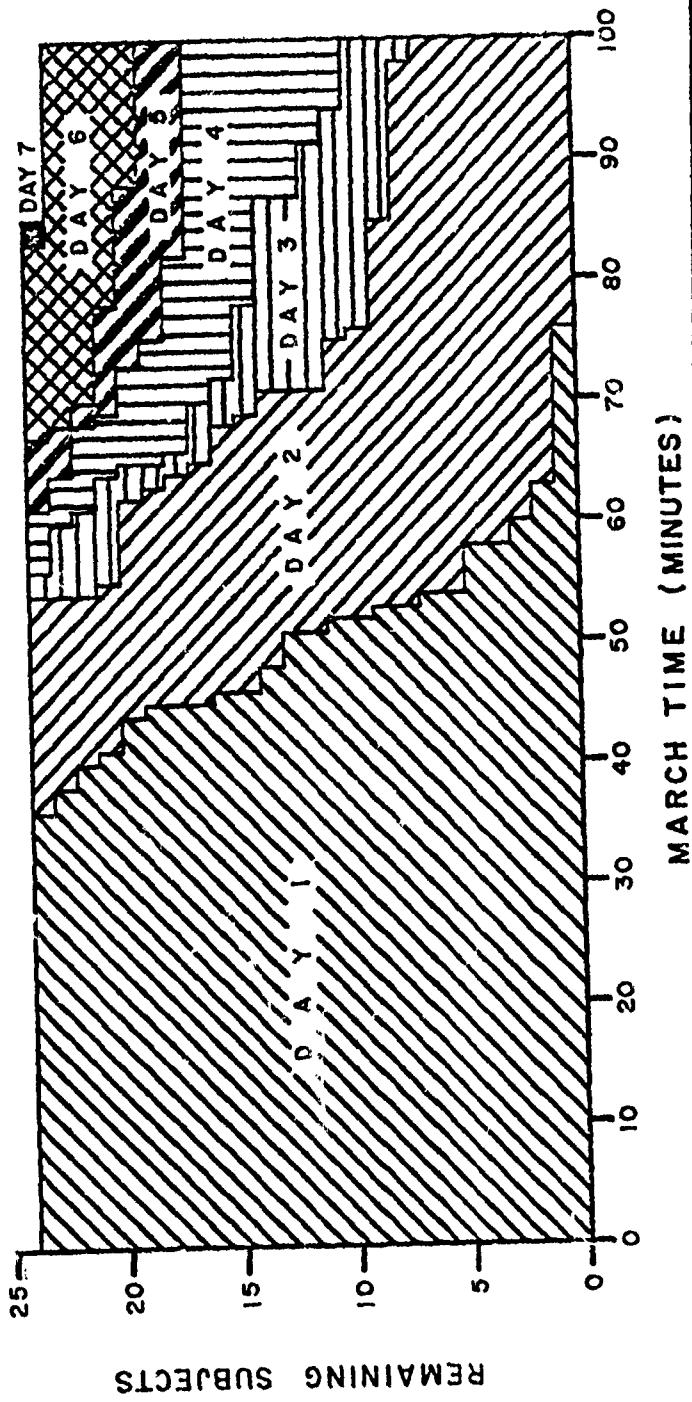


Figure 1. Work tolerance during seven days of heat acclimatization exposure, marching at 5.6 km/h (3.5 mph) for 100 minutes at 49°C (120°F), 20% RH.

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that, with the massive sweating, a more dilute sweat is produced which serves to conserve the body's sodium; this mechanism can be at least partially evoked simply by acute restriction of dietary sodium intake, without work or heat.

The benefits of sweat gland conditioning are, of course, a greater benefit in a hot-dry (desert) environment than they would be in a hot-wet one (jungle or the microclimate within a chemical protective clothing system) where evaporative cooling is less limited by sweat availability than by the limited capacity of the humid air to hold additional moisture (16).

DEHYDRATION:

Dehydration produces as dramatic a degradation of work performance in the heat as acclimatization produces an enhancement. As outlined above, water intake in amounts adequate to replace sweat losses can involve supplying 24L/day. As air temperature exceeds $\sim 30^{\circ}\text{C}$ (86°F), even an unclothed man begins to have difficulty eliminating his resting heat production ($1 \text{ MET} = 50 \text{ kcal/m}^2 \cdot \text{hr}$ or, for an average 70 kg soldier = 90 kcal/h) solely by radiation and convection; as air temperature $\geq 35^{\circ}\text{C}$, all the heat produced by the body must be eliminated by evaporation of sweat. Heat produced by the body during work (15 kcal/min for short periods during an assault) must be either eliminated from the body or stored in it, with body temperature rising $\sim 1^{\circ}\text{C}$ (1.8°F) for every 60 kcal that must be stored. Heat storage of 80 kcal is the usual voluntary tolerance limit, while heat storage levels of 160 kcal, incurred during some of our field operations, resulted in a 50% risk of heat exhaustion collapse; almost no one could continue with body heat storage > 240 kcal (when body temperature would be above 41°C). Each gram of sweat evaporated carries away ~ 0.6 kcal of heat, so evaporation of 1L/hr - the maximum sustainable sweat rate - can compensate for 600 kcal/hr of heat production; this is also about the maximum sustainable one hour work rate for an average man. However, if the sweat is not evaporated at the skin surface, the body does not get the full cooling benefit; with reduced permeability uniforms (e.g., the Std B chemical protective clothing system) the body cooling may be only 300 kcal per liter of sweat, produced at the skin, but evaporated at various points between the skin and clothing surface.

Clearly, the demands for drinking water pose a serious logistics problem. Troops can partially compensate for inadequate replacement of sweat losses, up to a point, by limiting their subsequent work, avoiding exposure to sunlight, or in hot crew compartments, and performing essential work during the coolest parts of the day or

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night - if the mission and the enemy allow this. However, Adolph (1) and others (10) have clearly documented the effects of dehydration on military performance. Failure to replace 700 ml of sweat loss (i.e., less than one hour's maximum sweat production) produces a 1% dehydration for an average 70 kg (154 lb) soldier. Man may have an extra 1.5L of body water available, since dehydration levels up to 2% seem to produce little problem. However, more severe dehydration clearly limits performance of hard work; a 6% dehydration (a shortfall of only 4.2L), incurred rapidly (i.e., over 6 to 8 hours, so that the body does not have time to partially adapt by intercellular dehydration) results in a non-effective fighting man. For longer exposures (2-5 days) water deficits greater than 10% are intolerable (1,10) and death occurs with 15 to 25% dehydration.

The availability of drinking water will not necessarily insure adequate ingestion. Troops given adequate water supplies have incurred "voluntary dehydration" levels of 5% or more. Thirst apparently is not an adequate stimulus to avoid such "voluntary dehydration", particularly under the pressures of field operations, and there are often problems of palatability because of the water temperature or pretreatment for purity (1). Thus water discipline, which formerly implied command control to limit water intake, today implies that Commanders, by direction, example and supervision at the squad or fire team level, must insure that adequate water is ingested. Small amounts, drunk frequently (e.g., every 20 to 30 minutes), are much better and produce less problems than infrequent large quantities, which may not be well retained. Reports on field trials from Israel, South Africa and the U.K., where heat acclimatized, fit troops were divided into 3 groups, the first given no water, the second with water ad lib and the third required to replace the sweat loss as measured at each halt, all agree that a march which cannot be completed by most men without water, and may be completed only with difficulty when water is given ad lib, can become almost routine when sweat losses are completely replaced.

PREDICTING EFFECTS OF HEAT ACCLIMATIZATION AND DEHYDRATION:

The factors limiting human tolerance for work in the heat are well understood (7). We have developed, and validated (8) a comprehensive model to predict the metabolic heat production (3,13) and the rectal temperature (4) and heart rate (5) responses to work, environment and clothing of fully acclimatized, well hydrated troops. Using the extensive data base on the changes in these responses during acclimatization, that has been built up at Natick during more than

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20 years of acclimatizing hundreds of men for chamber studies and field operations, and additional data from the extensive literature on heat acclimatization, a subroutine was developed (6) to include the range of zero to full (i.e., seven days) heat acclimatization in this prediction model. A literature search and a number of in-house studies on the effects of varying levels of dehydration were also conducted and these effects are now (11) also able to be incorporated in our predictions of performance during military operations in hot environments.

The basic model postulates the existence of a final, equilibrium deep body temperature (T_{re}) at which the body could balance its heat production [and environmental radiant and convective ($HR+C$) load if skin temperature (T_s) is less than the temperature of its surroundings (T_a)] with its total heat losses by evaporation of sweat [and by radiation and convection if $T_s > T_a$]. The model begins (4) at a basic T_{re} of 36.75°C ; work produces a T_{re} increase of $0.4^{\circ}\text{C}/100 \text{ kcal}$ of metabolic heat production (M); $HR+C$ increases or decreases T_{re} in direct proportion to the insulation of the uniform (clo) and the difference ($T_s - T_a$); evaporative cooling occurs as an exponential function of the difference between the required evaporation (i.e., $M \pm HR+C$) and the maximum possible evaporation allowed by (a) the evaporative permeability of the uniform worn (i_m/clo) and (b) the difference between the vapor pressure of sweat at the skin (P_s) and in the air (P_a). The rectal temperature at which such an equilibrium could be established may or may not be compatible with life, let alone continued performance; nevertheless, in both the model and real life, the rectal temperature will be inexorably driven toward this equilibrium T_{ref} (4) until heat stroke occurs (at $T_{re} > 41^{\circ}\text{C}$) or until heat exhaustion intervenes. The latter is primarily a function of heart rate (maximum heart rate = 220 b/m minus age, in years), and the model (5) exploits the link between rectal temperature and heart rate (HR) to predict heart rate in the heat during rest, work or recovery, with an experimentally determined, standard error of estimate of six beats per minute for groups of four or more heat acclimatized, well hydrated men. Response time delay factors, and rates of rise, for T_{re} and HR during rest, work and recovery have been developed and included in the model.

The adjustments for heat acclimatization involve a slight decrease (at most $\sim 0.5^{\circ}\text{C}$) in the initial, resting rectal temperature (T_{re0}) with heat acclimatization, a loss of 1/2 day of heat acclimatization status for every day without working in the heat, a difference of about 1.7°C in the T_{ref} between unacclimatized (0 days) and fully acclimatized (7 days) troops (i.e., 1.5°C plus the 0.2°C decrease in

T_{re0}), but little or no difference in the time constants for rest, work or recovery (6). In summary, unacclimatized troops start with a little higher body temperature ($\sim 0.2^\circ\text{C}$) and move toward higher T_{ref} levels (by a total 1.7°C) in about the same time as acclimatized troops; they therefore suffer a more rapid rise in T_{re} . There is little or no difference with or without acclimatization in initial heart rate but, despite the difficulty in estimating differences in heart rates which are well beyond the maximum rates than can occur (i.e., $>220 \text{ b/m}$), it appears that the greatest difference in heart rate with or without acclimatization is about 40 b/m . The time pattern of heart rate response depends, without reference to acclimatization, on the available cooling power (4) of the environment. In summary, heart rate responses without acclimatization simply reflect the more rapid rise (and thus earlier collapse) associated with the greater strain on the cardiovascular system of attempting to achieve an equilibrium heart rate level of up to 40 b/m above that for a fully acclimatized man. Note that under conditions of extremely high humidity (whether in the natural environment or the microclimate within clothing or crew compartments), the difference between fully and non-acclimatized subjects decreases and reflects primarily the small difference in initial T_{re0} ; one should, in fact, expect little or no benefit from the additional sweat production associated with heat acclimatization if the sweat could not be evaporated (16).

The adjustments for dehydration that have been adopted are somewhat simpler. While these may be changed in the future, subject to additional validating studies, it should be noted that the adjustments for dehydration derived, independently, from several studies did not differ meaningfully, despite the fact that they were conducted with different subjects and levels of dehydration over a two year period. Hydration, over the $+3$ to -6% range studied, does not appear to alter the equilibrium (i.e., final) T_{re} level very much, if at all. The increase amounts, at most, to one percent, per percent dehydration, of the total difference for the fully hydrated state between the initial (T_{re0}) and equilibrium (T_{ref}) rectal temperature; i.e., if T_{ref} , fully hydrated is 39.35°C [i.e., 36.75°C basic + 2.6°C from M , H_{R+C} and (E_{req} - E_{max}) functions], then with 5% dehydration, T_{ref} would only be increased by $.13^\circ\text{C}$ (i.e., $.05 \times 2.6$) and this is a meaningless difference. As might be expected, the effects of dehydration on heart rate are more impressive, with the index of heart rate used to compute the actual heart rate increased by 6% per percent dehydration. The time patterns for rates of rise of both rectal temperature and heart rate are also dramatically increased by dehydration, about 10% per percent

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dehydration; recovery after work is delayed exponentially, with a 6% dehydration almost doubling recovery time.

APPLICATION OF THE MODEL:

Two field studies, one involving U.S. and the other U.K. troops have been selected for examples of how this predictive model can be used for analysis. The U.S. study (9), a controlled field trial, involved a paratroop platoon, first physically conditioned by walking 8.7 km (14 miles) per day, then all exposed to one day (T1) of a one hour march at 5.6 km/hr at 40°C (105°F) 50% RH. The men then divided into two groups; an "unacclimatized" control group continued to train by marching 8.7 km/day for 12 days (interrupted for weekends) at 18°C (65°F), 50% RH; the other half of the platoon performed the same march at increasing temperatures, the first three days at 40°C, the next at 43.3°, the next at 46° and the last three at 49°C. All men were then exposed again (T2) to the one hour, 5.6 km march at 40°C, 50% RH. The actual difference in rectal temperatures after 45 minutes of T2 was 0.14°C between the heat acclimatized troops and those that simply had been physically conditioned; assuming, as indicated above, that physical conditioning imparts the equivalent of 3 days of heat acclimatization, the predicted difference at the end of 45 minutes is 0.16°C (for the march rate, load carried, uniform worn and environmental exposure used in this chamber phase of the study). The entire platoon was then flown to Fort Kobbe, C.Z. and the next day marched as a unit over an 11 mile trail course at 6.4 km/hr (4 mph), with 10 minute "rest breaks" each hour, during which rectal temperature and heart rate measurements were taken. The model was programmed to predict rectal temperature during the march; the reported T_A (31.1°C/88°F), RH (54%), uniform (fatigues), load (9 kg + clothing), work schedule (50' march, 10' rest) and adequate water (0% dehydration) were used and a dirt terrain (terrain factor 1.1 compared to 1.0 for a blacktop road), 1% grade and 0.89 m/s (2mph) wind were assumed. The predicted rectal temperature responses for troops with 7 days of acclimatization, and with the equivalent of 3 days (induced by physical conditioning), are shown in Figure 2. Despite the confounding of the fact that the actual data was measured during the 10 minute rest, when it is predicted that rectal temperatures should have been dropping rapidly, both the absolute levels of predicted temperatures and the predicted difference between the acclimatized (7 day) and non-acclimatized but physically conditioned (\approx 3 days) troops show good agreement between the predicted values and those measured 15 years ago.

The data base for the U.K. Study, an operational field

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11 Mile Platoon March

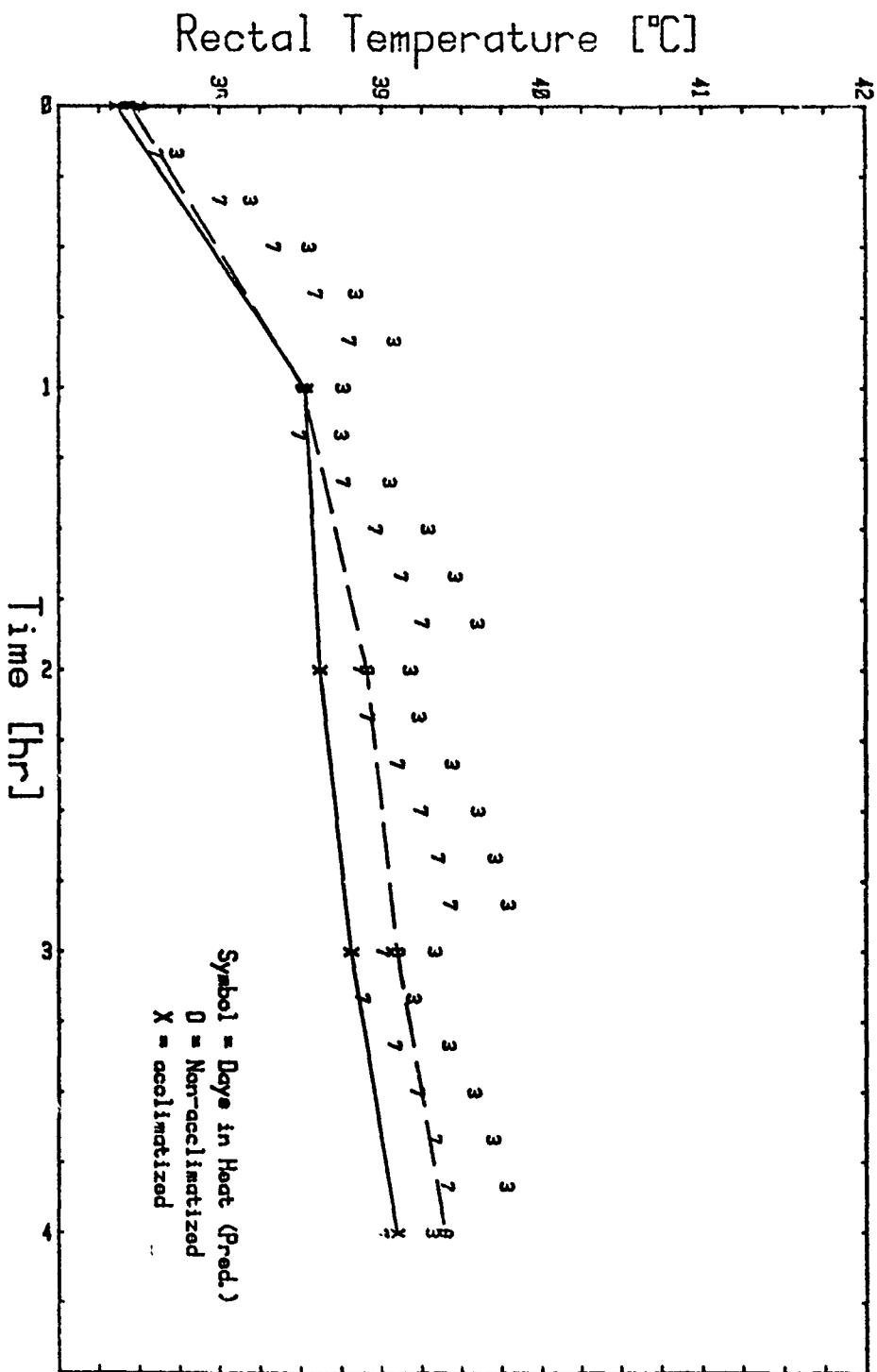


Figure 2. Observed (lines) and predicted (3,7) T_{re} for fully and non-acclimatized troops

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trial on the effects of travel fatigue and tropical conditions on the military efficiency of unacclimatized parachute troops during the first three days (14), is less adequate for prediction. The troops were of varied fitness and were judged to be slightly below the average of the Regiment from which they were drawn. Only task performance, casualty occurrence and morale were assessed and march rate was not uniform during the 22.5 km (14 mile) marches which were supposed to be completed in four hours; the march started within 7 hours of the landing in Singapore after a 43 hour flight with "rest" times of from 7-1/2 to 14-1/2 hours (average of 11 hours); state of hydration is uncertain, with ~15% vomiting; by the end of the second hour, 25% of the 51 men participating were "in difficulty", and 10% had already been withdrawn; there were more problems with the soldiers feet than with the heat. Accordingly, while the best estimates for the various input parameters to the model were selected using the actual field operation, the projected results primarily present the opportunity to contrast the effects of zero and three days of heat acclimatization with and without progressive dehydration incurred during the march.

A constant march rate (6.4 km or 4 miles per hour) over a dirt road (1.1 terrain factor), with 30 kg loads at 29.4°C (85°F), 70% RH, were used as inputs to predict rectal temperature (Figure 3) and heart rate (Figure 4) responses of average troops without acclimatization and with 3 days of acclimatization (whether induced by prolonged physical conditioning or by 3 days of heat acclimatization), without dehydration, or with progressive dehydration (1st hour = 0, 2nd hour 1%, 3rd hour 2% and 4th hour 3%) either as a result of inadequate water availability or inadequate command control to insure that sufficient water is drunk to replace sweat losses. The clear separation of the four curves, and reflection on the fact that T_{re} levels above 39.5°C and HR levels approaching 180 b/m are incompatible with continuation of activity, provide a strong recommendation for optimum physical condition, heat acclimatization and hydration of troops expected to operate effectively during their first battle in the heat.

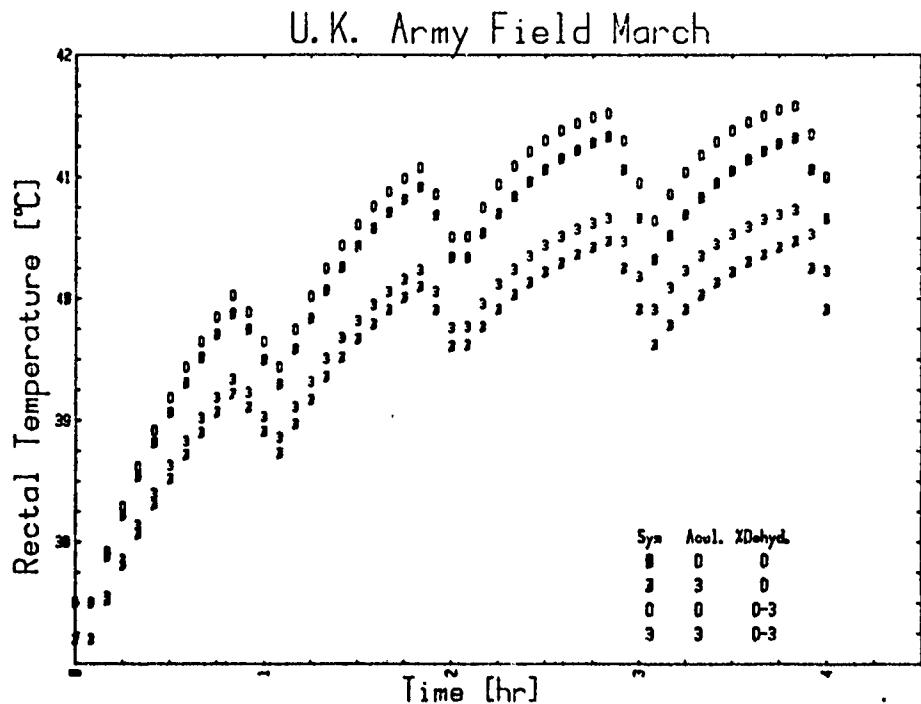


Figure 3. Tre w and w/o partial acclimatization and dehydration

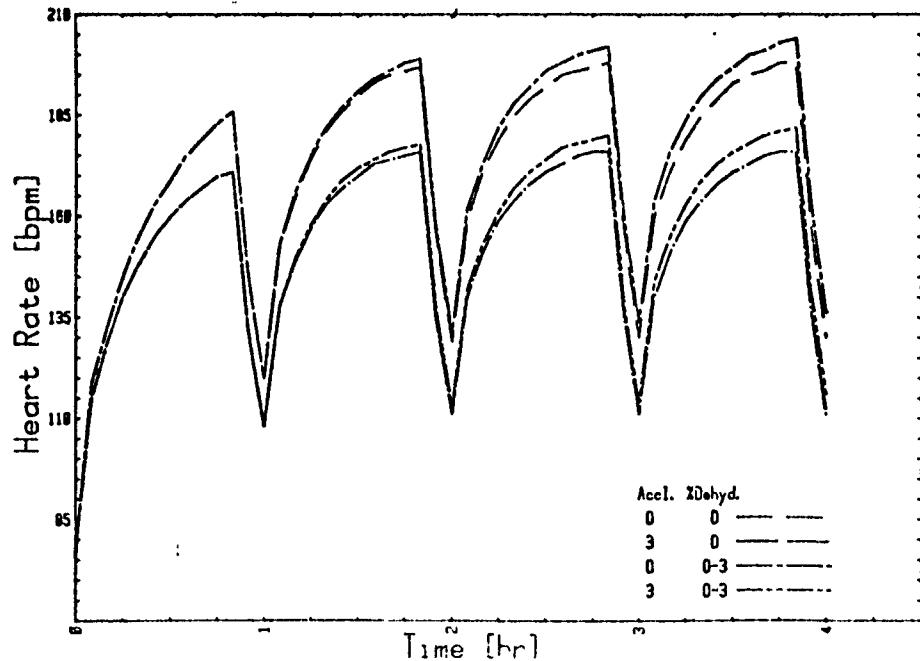


Figure 4. H.R. w and w/o partial acclimatization and dehydration

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Heat tolerance, Heat acclimatization, Dehydration, Prediction models, Operational performance		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) There are two major physiologic requirements for optimum performance of troops during their initial actions in a hot theater of operation; previous heat acclimatization and previous planning for delivery and ingestion of adequate water. Heat acclimatization requires about 7 days, with about 2 hours each day spent doing moderately hard to heavy work under conditions at least as hot as those anticipated; lower levels of exertion and/or heat stress produce only partial acclimatization. Adequate replacement of body water, lost as sweat is 040 850		

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also essential to prevent early physical and/or heat exhaustion of the troops. The USARIEM heat casualty prediction model (HEATCAS), developed to predict the physiological responses and their operational impact for acclimatized, well hydrated troops, has now been expanded to include the responses of unacclimatized troops, their improvements with acclimatization, the estimated drinking water requirements and the effects of failure to provide the required water. The model provides tabulated and graphical predictions of the benefits of heat acclimatization and the costs of dehydration on operations under any specified combination of climate and terrain. Some previous military operations, where inadequate initial acclimatization or water intake produced operational problems are compared with the USARIEM model predictions.

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